

## **Task 2 Report – Close Minor Research Gaps**

# **Feasibility of Nonproprietary Ultra-High Performance Concrete (UHPC) for Use in Highway Bridges in Montana: Implementation**

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## **1 Introduction**

Ultra-high performance concrete (UHPC) has mechanical and durability properties that far exceed those of conventional concrete. However, using UHPC in conventional concrete applications has been cost prohibitive, with commercially available/proprietary mixes costing approximately 30 times more than conventional concrete. Previous research conducted at Montana State University (MSU) has focused on the development and evaluation of nonproprietary UHPC mixes made with materials readily available in Montana. These mixes are significantly less expensive than commercially available UHPC mixes, thus opening the door for their use in construction projects in the state. The focus of the proposed project is on taking this material beyond the laboratory, and successfully using it on a bridge project in Montana, specifically for field cast joints. This project is a required step to fully understand and capitalize on the benefits of using UHPC for this application and increase the performance, durability, and efficiency of Montana bridges.

The specific tasks associated with this research are as follows:

Task 0 – Project Management

Task 1 – Literature Review

Task 2 – Close Minor Research Gaps

Task 3 – Bridge Construction and Related Activities

Task 4 – Monitoring Bridge Performance

Task 5 – Analysis of Results and Reporting

This report documents the work completed as part of Task 2 – Close Minor Research Gaps.

## **2 Background**

Previous research at MSU developed a nonproprietary mix design that has a 28-day compressive strength of 18 ksi, and is significantly less expensive than proprietary UHPC mixes [1, 2]. The focus of this project is on the field implementation of the MT-UHPC developed in this initial research. Specifically, the MT-UHPC was used in two bridges on Highway 43 near Lost-Trail Pass outside of Wisdom, MT. The MT-UHPC was used to connect precast pile caps to steel piles, and was used in longitudinal joints between precast/prestressed hollow-core bridge beams. A few minor research gaps in the mixing/placing/curing procedures of the MT-UHPC needed to be filled prior to its use in the bridge project discussed above. This report documents the results of this work focused on filling these gaps.

## **3 Scope of Report**

This task investigated the effects of varying the mixing process, batch size, and mixing and curing temperatures. It also included the development of a maturity curve to be used in determining the strength of the UHPC in the field.

It should be noted that this investigation was conducted using the exact materials and mixers to be used by the contractor in the actual bridge project. The mix proportions used in the MT-UHPC are provided in Table 1. More details on the specific materials used in this project will be provided in the final report. However, a brief summary of materials are included here. The cement was a Type I/II/IV from the GCC cement plant

in Trident, MT. The fly ash was a Class F ash sourced from Prairie State Energy Campus in Marissa, IL. The silica fume was MasterLife SF 100 from BASF. The fine aggregate was a masonry sand processed and packaged by QUIKRETE near Billings, MT. The high range water reducer (HRWR) was CHRYSO Fluid Premia 150, which is a polycarboxylate ether (PCE)-based product. The steel fibers were sourced by Hiper Fiber and were 13 mm long, had a diameter of 0.2 mm and a tensile strength of 285 ksi.

Table 1: Mix Proportions for 1 yd<sup>3</sup>

Item	Weight (lbs)
Water	298.7
Portland Cement	1299.5
Fly Ash	371.3
Silica Fume	278.4
HRWR	64.4
Steel Fibers	262.9
Fine Aggregate	1556.4

Table 2 provides a brief summary of the mixes conducted as part of this task. It should be noted that the recorded strengths were obtained from the average of three 3-by-6 in cylinders. Each of these mixes will be discussed in greater detail in the following sections.

Table 2: Summary of MT-UHPC mixes

Mix Number	Description	Batch Size (cuft)	Ambient Temp (°F)	Cure Temp (°F)	24-hr Strength (ksi)	28-day Strength (ksi)
1	Baseline mix using materials sourced from the contractor	2.5	48	70	6.9	18.4
2	First of two consecutively mixed batches	2.5	67	70	6.8	16.4
3	Second of two consecutively mixed batches	2.5	67	70	7.3	17.8
4	First 4.5-ft <sup>3</sup> batch	4.5	57	70	7.7	17.1
5	Mix that investigated a new mixing method of adding 2/3 <sup>rd</sup> of dry material with water, then adding the remaining dry material after turnover	4.5	61	70	9.53	17.4
6	A failed 4.5-ft <sup>3</sup> mix that stiffened up in the mixer	4.5	63	70	6.5	13.7
7	Mix that investigated the effects of curing cylinders under varying temperatures	3	67	70 Varying (56-93)	7.3 8.7	17.2 ---
8	Mix investigating replacing 40% of the mix water with ice to combat temperature effects	3	86	70	7.9	20.1
9	Mix investigating temperature effects by curing cylinders in hot, cold and room temperature conditions for varying amounts of time.	3	45	34 70 100	0.4 5.9 11.8	12.4 17.8 18.6

## 4 Mixing Methods

The effects that several mixing and batching procedures have on the performance of the MT-UHPC were investigated in this research. Each bridge discussed above will require approximately 5 yds<sup>3</sup> of UHPC, which will amount to approximately 30-45 batches per bridge (depending on batch size) using the mixers available for this work (Imer-Mortarman 360s). Obviously, batching and mixing this quantity of mixes will be time consuming, and any effort to reduce this time should be investigated. This research specifically investigated the effects of conducting consecutive batches without washing out the mixers, and the effects of varying the batch size. The results of these trial batches are summarized below.

### 4.1 Consecutive Batches

All previous research on the MT-UHPC was conducted on single batches of UHPC with a clean mixer. This research investigated the effects of conducting consecutive mixes, without cleaning the mixer between

batches. In this investigation, two mixes were performed in succession, and turnover time, flow, and strength gain were recorded. The first mix (initiated in a clean mixer) turned over at approximately 3 minutes and had a flow of 11.25 in. The second mix (initiated in a mixer with residual UHPC from the previous mix), had a turnover time of approximately 7 minutes and a flow of 11 in. While there is some variation in turnover time, this variation is in the range of what was observed throughout this research. The recorded strengths from each mix are provided in Figure 1. These results indicate that conducting consecutive mixes has a very minor effect on the performance of the MT-UHPC, and therefore this may be a viable option to reduce the total time required to cast the MT-UHPC on the bridge projects. However, it should be noted that only two batches were conducted consecutively, and the effects of conducting more than two batches was not investigated. That being said, nothing in the process indicated that this would be a problem. Further, to prevent buildup on the mixers, they should be inspected and cleaned accordingly throughout the process.

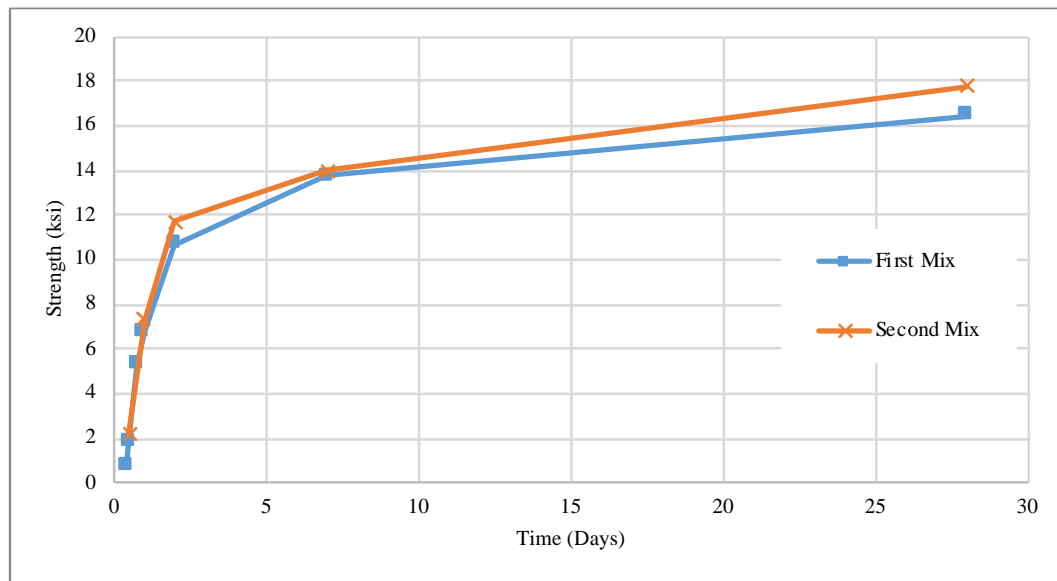


Figure 1: Strength gain of consecutively mixed batches

## 4.2 Batch Size

UHPC is typically mixed in high-shear pan mixers, and requires a significant amount of power during the mixing process. The mixer can bog down and possibly stall after water is added to the dry ingredients and before the mix turns over and becomes fluid. Therefore, UHPC is typically mixed in smaller batch sizes than are required for conventional concrete, and as an approximation, Graybeal [3] recommends using a batch size in a particular mixer that is half the capacity of what would be used for conventional concrete or grout.

As mentioned previously, this research and the bridge projects will use Imer Mortarman 360 high-shear pan mixers for mixing the MT-UHPC. These mixers have a stated capacity of 9 ft<sup>3</sup>; however, as discussed above it would not be feasible to mix this amount of UHPC in these mixers. Previous research at MSU conducted several trial batches using these mixers with varying volumes of MT-UHPC (from 2.5 to 4 ft<sup>3</sup>), and determined that batch size did not have a significant effect on the performance of the mix, with no clear

trends in flow or compressive strength [2]. That being said, they do note that the constituent materials in the 4-ft<sup>3</sup> batch were near the top of the mixer prior to the mix turning over and that larger batches may be possible, but modifications to the mixing process may need to be explored. This current task investigated the feasibility of scaling the batch size up to 4.5 ft<sup>3</sup> (half of the mixer capacity), to reduce the number of batches required in the bridge projects and subsequently the amount of time required for placement.

As part of this investigation several 4.5-ft<sup>3</sup> batches were mixed in the lab, and the flow and resultant compressive strengths were obtained. The first 4.5-ft<sup>3</sup> batch conducted in the lab performed well during the mixing process, with no major issues. Although, the mixer did bog down some, and the constituent materials were slightly overflowing from the mixer after the water was added and prior to the mix turning over (Figure 2). The resultant flow was 11.25 in and the 28-day compressive strength was 17.1 ksi. The strength gain profile for this mix is compared to that of a typical 2.5-ft<sup>3</sup> batch in Figure 4, and the results are consistent.



Figure 2: Mix constituents nearly overflowing during a 4.5-ft<sup>3</sup> batch

An additional 4.5-ft<sup>3</sup> mix was performed to confirm that this batch size would be suitable for the bridge projects. However, this additional mix did not perform well. The mixer bogged down and stalled during mixing, which led to the mix prematurely stiffening up in the mixer. The mix became too stiff to cast cylinders and was not suitable for placement. Figure 3 shows a beam being cast with the successful 4.5-ft<sup>3</sup> mix (left) compared to the stiffened unsuccessful mix (right).

(a) successful 4.5 ft<sup>3</sup> batch being placed(b) unsuccessful 4.5 ft<sup>3</sup> batch being placedFigure 3: First two 4.5-ft<sup>3</sup> batches being placed into beam molds

While the larger batch size was determined to be a major factor in this failed mix, elevated temperatures may also have contributed. As will be discussed in greater detail in the following section, elevated temperatures can be beneficial to UHPC in regards to strength gain, but it is well documented that mixing UHPC at elevated temperatures can be problematic [2, 4, 5]. It is worth noting that this failed mix was attempted on June 9<sup>th</sup> at 7 pm, when the outside temperature was 82°F, and the water and dry-mix materials were around 70°F. This is a higher temperature than any previous trial batch conducted in this research, and most likely contributed to the failure of the mix. It should also be noted that the temperature of the mix increased substantially while it was stiffening up due to the premature exothermic reactions taking place within the mix.

To further investigate the feasibility of using a batch size of 4.5 ft<sup>3</sup>, two additional 4.5-ft<sup>3</sup> batches were conducted in the lab. It should be noted that both mixes were conducted early in the morning to avoid elevated temperatures being a factor. The first of these mixes investigated a modified mixing procedure intended to reduce the strain on the mixer. This procedure involved (1) adding 2/3<sup>rd</sup> of the dry mix (cement, fly ash, silica fume, and sand), (2) adding all water and HRWR, and (3) adding the remaining 1/3<sup>rd</sup> of the dry mix after the mix turned over. This process was successful at reducing the initial strain on the mixer. After the initial portion of dry mix and water/HRWR were added, the mix quickly turned over without bogging the mixer down. That being said, once the additional dry mix was added the mix appeared to revert back to the pre-turned over state for several minutes before once again turning over and becoming fluid.

During this phase of the process, the mixer did bog down some, but it did not stall out as it did during the previous mix. The resultant flow and compressive strengths for this mix were adequate. The resultant compressive strengths are included in Figure 4. However, this process did not completely alleviate the strain on the mixer and would be labor intensive on the job site.

The final 4.5-ft<sup>3</sup> mix was conducted using the standard mixing procedure, during the early morning when temperatures were less than 65°F. This mix was not successful, once again stiffening up and stalling the mixer before the mix turned over. It should be noted that once again the temperature of the mix increased substantially while it was stiffening up due to the premature exothermic reactions taking place within the mix. Additional water was added to the mix in an attempt to increase the flow, but this was unsuccessful. The mix was workable enough to cast cylinders, but the resultant 28-day strengths were the lowest recorded in this research, 13.65 ksi.

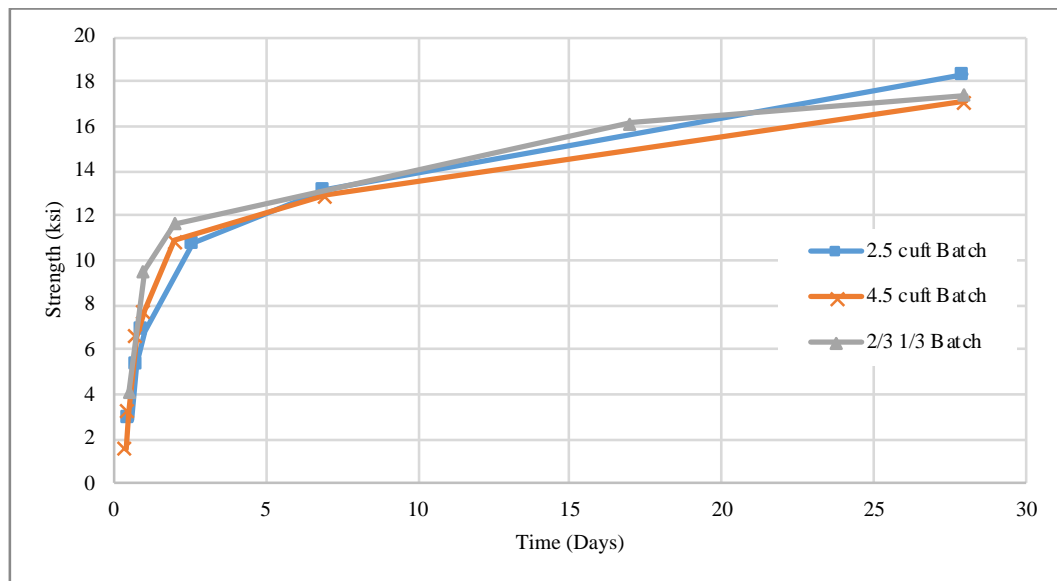


Figure 4: Comparison of compressive strengths from different batch sizes and mixing methods

After these mixes, the decision was made to limit the MT-UHPC batch size in the Imer-Mortarman 360 mixers to 3-ft<sup>3</sup> to avoid premature setting/stiffening and to limit strain on the mixers. It should be noted that while the modifications we made to the mixing process (withholding 1/3<sup>rd</sup> of the dry mix until turnover) did alleviate some (not all) of the strain on the mixers, this process would be labor intensive and be counteractive to the benefits of larger batch sizes. A method was proposed and successfully used by Michigan [5] in which a portion of the sand was withheld from the mix until the mix turned over. This method is not appropriate for the bridge projects in this research, as all of the dry ingredients will be premixed prior to arriving on site.

## 5 Temperature Effects

As stated in the previous section, temperature can have a significant effect on the performance of UHPC. High temperatures during the curing process can be beneficial relative to strength gain, but detrimental during the mixing process as elevated temperatures can cause increased evaporation of the limited mix water, and prematurely initiate the reactions within the UHPC. Issues with elevated temperatures were first

encountered with the second 4.5-ft<sup>3</sup> batch discussed in the previous section (Figure 3), which was conducted outside at a temperature of 82°F. The construction of the bridge is scheduled to take place summer/early fall in Wisdom, MT where temperatures can vary significantly throughout the day. Therefore, it is imperative to determine a range of outside temperatures suitable for mixing MT-UHPC and quantify the effects that curing temperature has on strength gain of MT-UHPC.

### **5.1 Temperature Range for Batching MT-UHPC**

Previous research at MSU investigated the effects of mixing MT-UHPC at low temperatures (40°F), and determined that there were no issues with workability and resultant compressive strengths at this low temperature [2]. While batching the MT-UHPC at a lower temperature is most likely possible, it was not specifically investigated in this research.

Elevated temperatures can negatively affect the batching of MT-UHPC, causing the mix to stiffen up significantly due to increased evaporation and premature reactions within the mix. Previous research at MSU investigated the effects of mixing MT-UHPC at an outside temperature of 75°F, when the constituent dry materials were at 90°F [2]. While this mix worked, its flow was significantly less than that of typical mixes conducted at lower temperatures (6.25 in vs. 10-11 in). Further, as discussed above, one of the mixes in this research was conducted at an outside temperature of 82°F, when the constituent materials were around 70°F. This mix stiffened up prematurely in the mixer, so much so that it was not possible to cast test cylinders or perform a flow test.

Previous research has successfully used ice to replace a portion of the mix water to allow casting UHPC at elevated temperatures [4, 5]. To evaluate the effectiveness of using ice to replace a portion of the mix water in MT-UHPC, a 3-ft<sup>3</sup> mix was conducted at MSU in the evening when the outside temperature was 86°F. For this mix, the dry material was stored outside in the shade for approximately 5 hours prior to mixing when temperatures were in the low 90s, and at the time of mixing, the dry-mix materials were 77°F. The mix water was 67°F, and 40% of the mix water was replaced with cube ice obtained from a local gas station. The mixing was carried out in the shade. The mix performed well, did not set prematurely, had a flow of 10 in, and had adequate strength gain (shown in Figure 5 in comparison to the MT-UHPC mix conducted at lower temperatures). That being said, it did take a few more minutes to turn over, as it took some time for the ice to melt and contribute to the mix. Further, the mix did begin stiffening up after turnover more quickly than previous UHPC mixes conducted at lower temperatures. Also, it was observed that the UHPC taken into the air-conditioned lab to cast specimens remained workable longer than the UHPC that remained outside of the lab at elevated temperatures. This quicker setting phenomenon may be an issue when trying to place UHPC into the keyways of the slab (where flow is important) if the slab temperature is elevated due to direct sunlight.

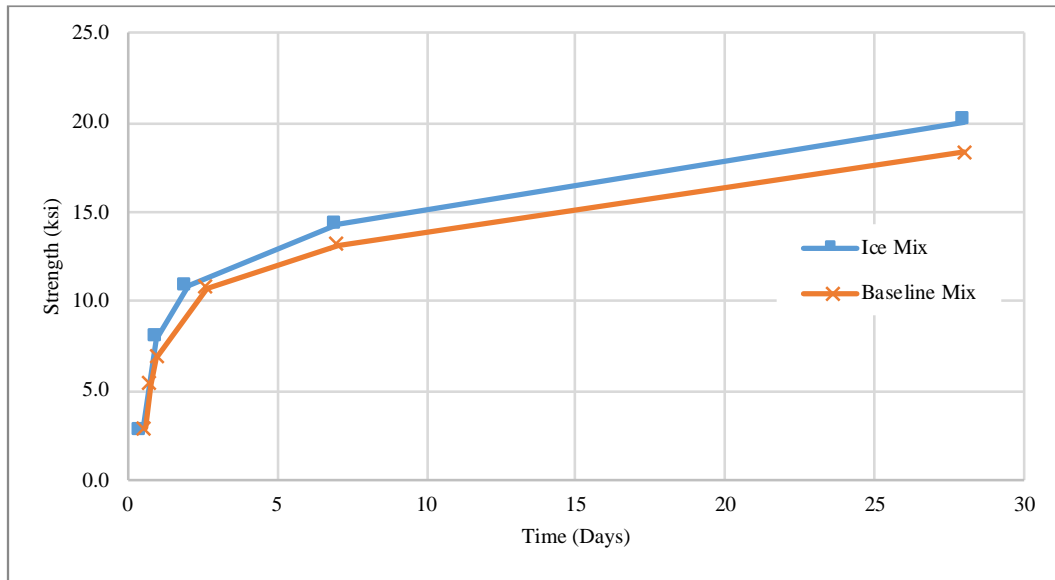


Figure 5: Compressive strengths of ice mix versus conventional mix

The MT-UHPC should be placed at lower outside temperatures and when material temperatures are low. If MT-UHPC is to be placed at higher temperatures, care should be taken to reduce the risk of the mix prematurely setting. The current specifications for the MT-UHPC states that it should not be placed when outside temperatures are above 80°F. While this limit is a good starting point for dealing with elevated temperatures, other factors should also be considered and mitigated. For example, the MT-UHPC dry-mix material should be protected from the sun and elevated temperatures prior to mixing. Further, the mixers should also be protected from the sun, as their temperatures can far exceed the outside temperatures when exposed to direct sunlight. Additionally, the use of ice to replace a portion of the mix water could be used (as discussed above) to keep temperatures within the mix low.

## 5.2 Preliminary Investigation on the Effect of Curing Temperature on Strength Gain

A preliminary investigation was conducted to study the effects that curing temperature has on initial strength gain. In this investigation, cylinders were cured for the first 48 hours under two conditions. After casting at room temperature, one set of cylinders was cured outside of the lab in the sunlight where the ambient temperatures varied from 56°F to 93°F. The other set of cylinders was cured in the lab at a constant temperature of 70°F. The strengths from these mixes are compared in Figure 6. As can be observed in this figure, the cylinders cured outside exposed to elevated temperatures, gained strength significantly faster than the cylinders cured at 70°F. At 10 hours, the outside cylinders had a compressive strength of 5.7 ksi, while the cylinders cured inside were only at 0.5 ksi. At 48 hours, the difference in strengths was significantly less, but the outside-cured specimens were still higher (11.6 ksi vs. 10.5 ksi).

Following this preliminary investigation, the effect of curing temperature on strength gain (including long-term effects) was systematically investigated, as is discussed in the following section.

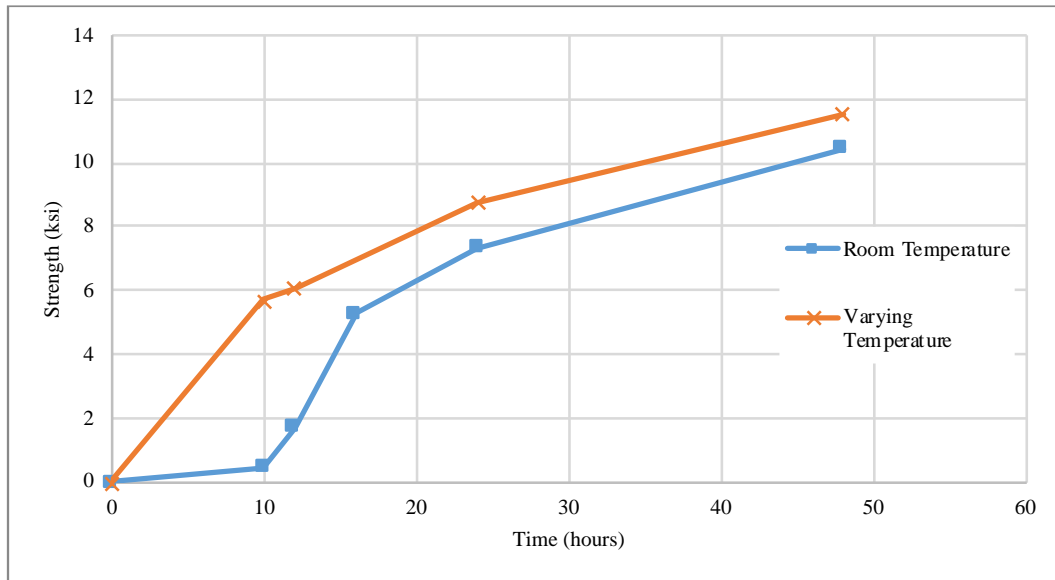


Figure 6: Compressive strengths from preliminary curing temperature study

### 5.3 Systematic Investigation on the Effect of Cure Temperature on Strength Gain

This study systematically investigated the effect of curing temperature on the strength gain of MT-UHPC over the first 28 days. In this study, a 3-ft<sup>3</sup> batch of MT-UHPC was mixed at room temperature within the lab and a total of 72 cylinders were cast. These cylinders were then separated into groups of 12, and cured at 3 different temperatures (34°F, 70°F, and 100°F) for either the first 48 hours or for the full 28 days. For example, one group of 12 cylinders was cured at 34°F for the first 48 hours and then transferred to the cure room for the remaining 26 days, and another group was cured at 34°F for the full duration. Compressive strengths were obtained at 24 hours, 48 hours, 7 days, and 28 days (3 cylinders x 4 test days = 12 cylinders). The test matrix and the resultant strengths (averages of 3 specimens) are summarized in Table 3. It should be noted that the cylinders cured at 34°F were placed within a temperature-controlled freezer in the Subzero Research Laboratory at MSU, the cylinders cured at 70°F were cured in the concrete materials lab, and that the cylinders cured at 100°F were placed within an oven in the concrete materials lab. Moisture was not provided or controlled for the specimens cured outside of the cure room.

Table 3: Summary of test results for systematic temperature study

Cure Condition (Initial 48hr)	Cure Condition (After 48hr)	24-hr strength (ksi)	48-hr strength (ksi)	7-day strength (ksi)	28-Day strength (ksi)
Freezer (34°F)	Cure Room (70°F)	0.37	3.57	14.43	17.00
Lab (70°F)	Cure Room (70°F)	5.93	9.57	14.37	17.77
Oven (100°F)	Cure Room (70°F)	11.77	13.43	14.07	16.10
Freezer (34°F)	Freezer (34°F)	0.37	3.57	9.90	12.40
Lab (70°F)	Lab (70°F)	5.93	9.57	13.87	16.87
Oven (100°F)	Oven (100°F)	11.77	13.43	14.73	18.60

The average compressive strengths for the cylinders cured at various temperatures for the first 48 hours and then moved to cure room for the remaining 26 days are shown in Figure 7. As can be observed in this figure and Table 2, curing temperature has a significant effect on initial compressive strength, with 24-hour strengths ranging from 0.37 ksi at 34°F to 11.77 ksi at 100°F, and 48-hour strengths ranging from 3.57 ksi at 34°F and 13.43 ksi at 100°F. However, after the cylinders are transferred to the cure room this trend of increasing strength with increasing initial cure temperature is not present. The strengths at 7 days are nearly identical to each other (around 14 ksi), and at 28 days the specimens cured at 100°F actually have the lowest strength. The latter indicates that the early strength gain observed for the 100°F may come at a cost of slightly lower long-term strengths.

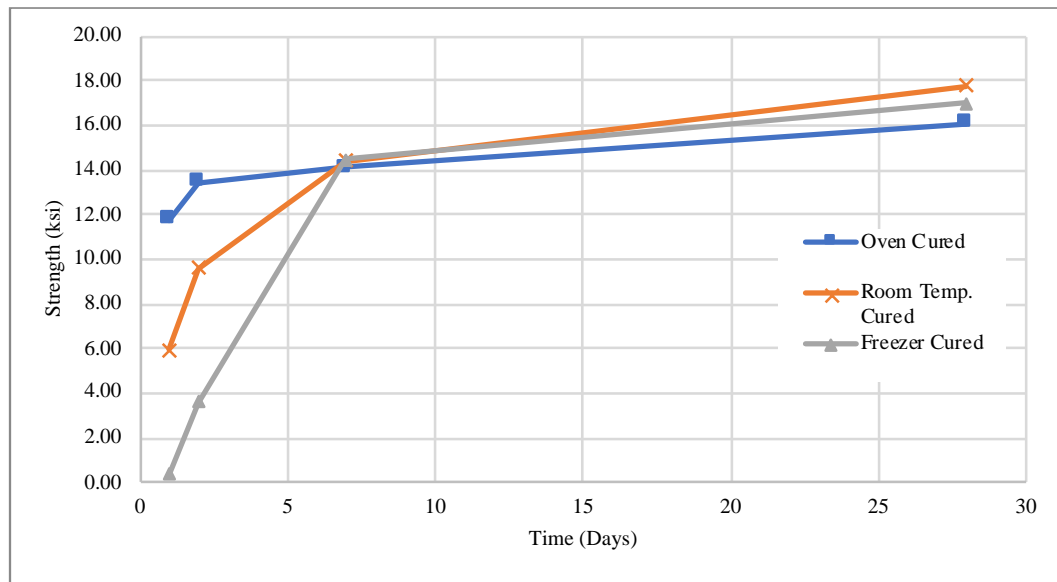


Figure 7: Compressive strengths from cylinders cured at various temperatures for first 48 hours before being moved to cure room

The average compressive strengths for the cylinders cured at various temperatures for the full 28 days are shown in Figure 8. As can be observed in this figure, and as expected, curing temperature has a significant effect on compressive strength throughout the testing period. At 28 days, the average compressive strengths were 12.4, 16.9, and 18.6 ksi at 34°F, 70°F, and 100°F, respectively. It should be noted that the 28-day strength at 34°F (12.4 ksi) was the lowest observed in this phase of research, while the 28-day strength at 100°F (18.6 ksi) was the highest.

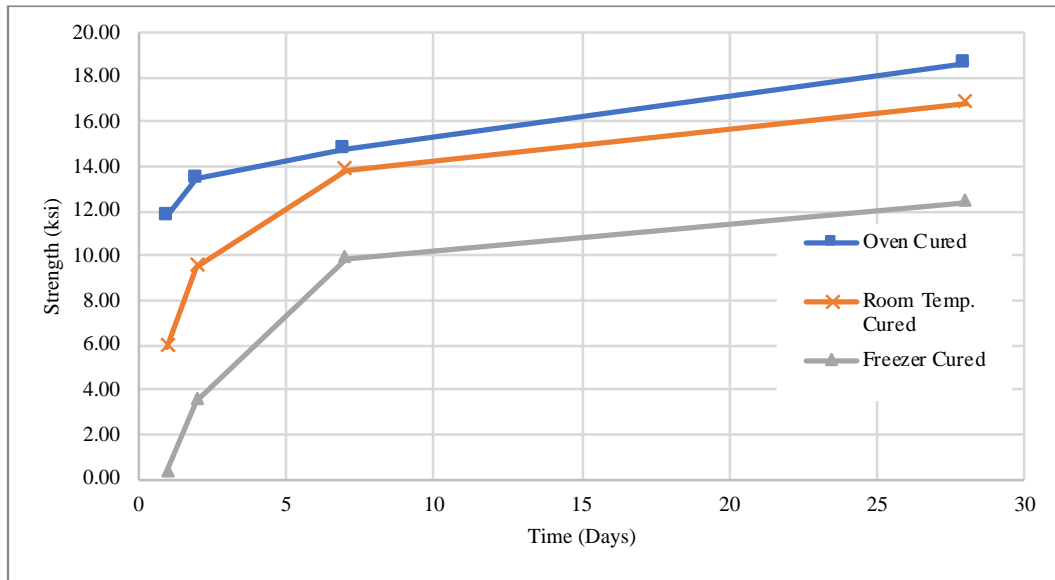


Figure 8: Compressive strengths from cylinders cured at various temperatures for duration of testing

## 6 Estimating Early Strength Gain with Maturity Method

As will be discussed in a later task report, each bridge to be constructed using MT-UHPC has a construction window of only 96 hours (including demolition of the existing bridges), and certain phases of the construction cannot proceed until the MT-UHPC has reached the minimum design strength. Therefore, it is imperative to estimate the early strength gain of the MT-UHPC, including the effects of curing temperature, as this was shown to have a significant effect on early strength gain in the previous section. This was achieved using the maturity method prescribed in ASTM C1074. Maturity curves were developed for several of the mixes discussed above (Mix 2, 3, 7, and 9 in Table 3), which were exposed to various curing conditions, and include the mixes focused on evaluating the effects of curing temperature. Maturity was monitored using a Humboldt Model H-2682 maturity meter, using the Temperature Time Factor (TTF) and an assumed temperature datum of 0°C (recommended by ASTM C1074). The curves were obtained by monitoring the TTF and corresponding compressive strengths of the mixes systematically throughout the curing process.

The resultant maturity curves for these mixes are shown in Figure 9 for the first 48 hours, and Figure 10 for the full duration of testing (assuming a datum of 0°C). As can be observed, the data for all of the mixes sans the mix cured at 34°F fell along the same general curve. While this good fit is promising, the outlying data for the 34°F specimens is somewhat concerning. This data shows that the strengths of the 34°F-specimens are significantly higher than what would be predicted with the other curves developed in this study, indicating hydration is taking place faster than anticipated at this temperature. This finding suggests that the assumed datum temperature of 0°C may not be appropriate for the MT-UHPC. To investigate this further, the recorded TTF values were adjusted to account for a datum value of -5°C rather than 0°C. The adjusted maturity curves using a datum of -5°C are provided in Figure 11 for the first 48 hours, and Figure 12 for the duration of testing. As can be observed, the maturity curves for the first 48 hours are now in better agreement, although the 34°F-curve is still predicting slightly higher strengths than the other curves.

Referring to long-term strengths (Figure 12), all curves are again very similar, although the 28-day strengths for the 34°F-specimens are lower than anticipated, with recorded strengths of around 12.5 ksi rather than the 13.5 ksi predicted by the other curves. While the adjusted datum temperature of -5°C provides closer agreement between the curves, the datum temperature should be investigated further using the methods outlined in ASTM C1074 Appendix 1.

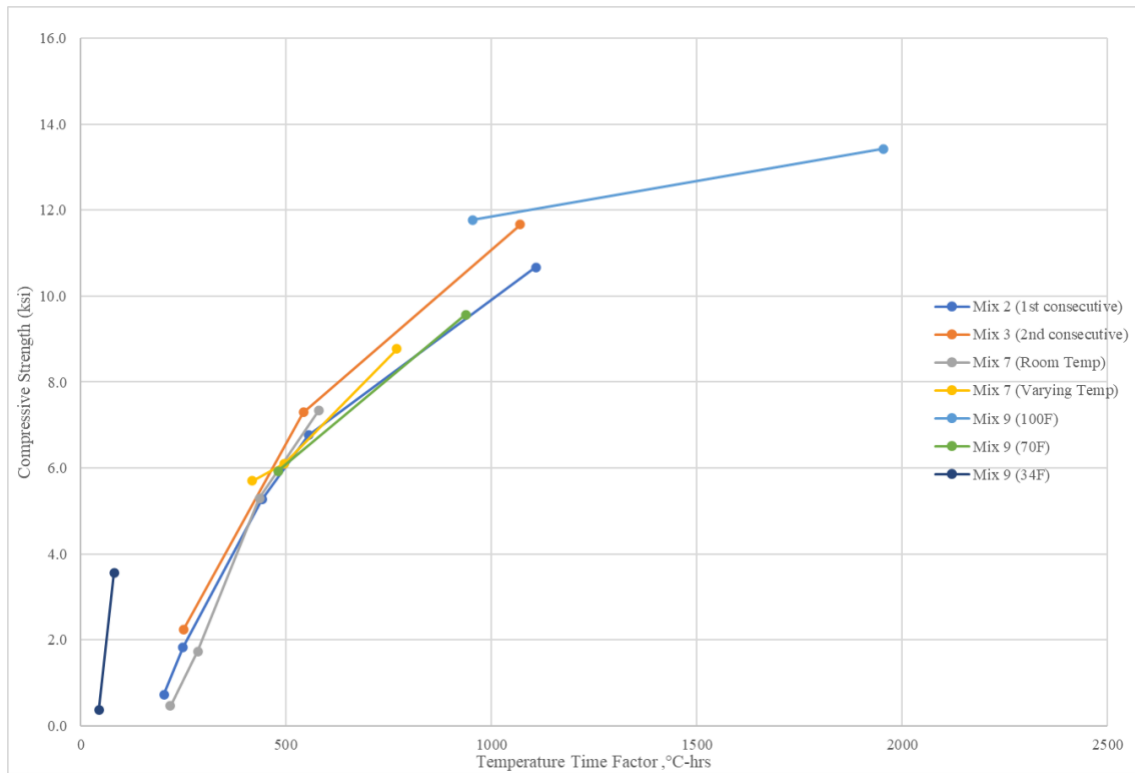


Figure 9: Maturity curves over first 48 hours (0°C Datum)

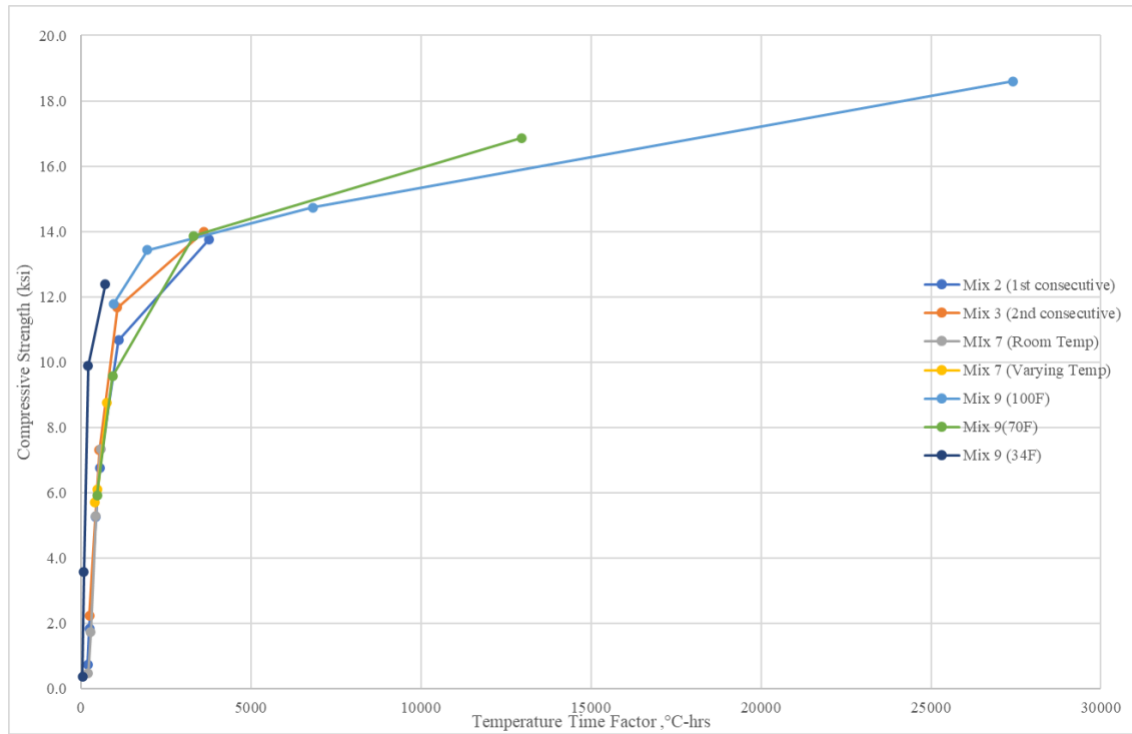


Figure 10: Maturity curves over duration of testing (0°C Datum)

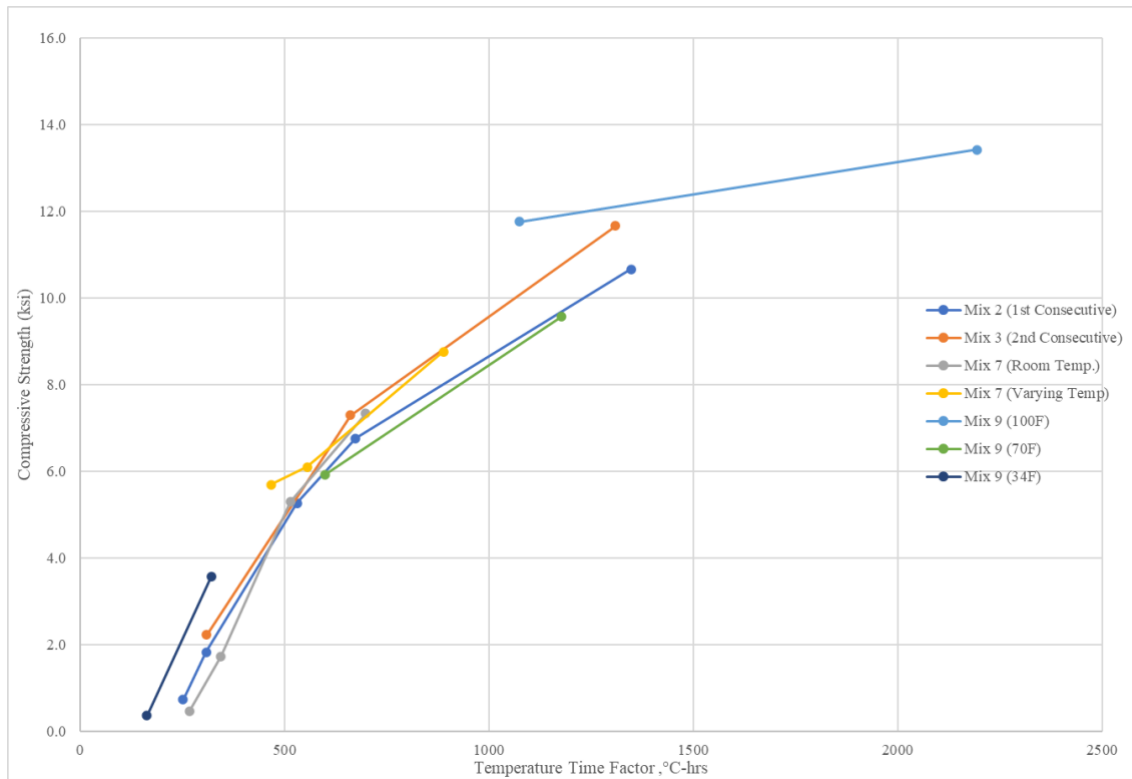


Figure 11: Maturity curves over first 48 hours (-5°C Datum)

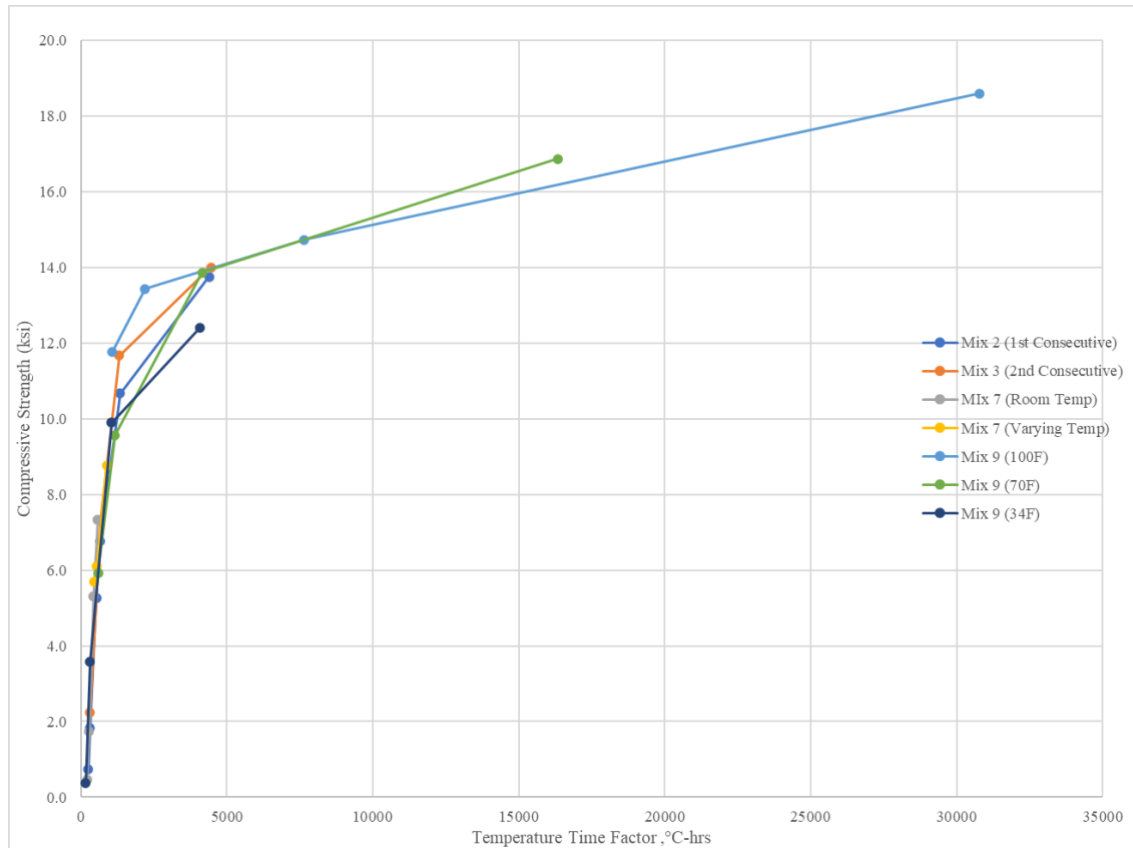


Figure 12: Maturity curves over duration of testing (-5°C Datum)

## 7 Summary of Research and Key Findings

This task was focused on filling several research gaps related to the field application of MT-UHPC. Specifically, this research investigated the effects of the mixing process, batch size, and temperature on the performance of MT-UHPC. It also developed maturity curves to be used in estimating the early strength gain of MT-UHPC. Key findings from this task follow.

- MT-UHPC batches can be mixed consecutively in the same mixer without cleaning the mixer between batches. Residual material and moisture in the mixer had little effect on the flow and strength gain. However, the mixers should be inspected and cleaned accordingly throughout the projects.
- Batch sizes should be limited to 3 ft<sup>3</sup> when mixing MT-UHPC with Imer Mortarman 360s. Batch sizes of 4.5 ft<sup>3</sup> using these mixers were problematic in this research, with two out of four batches prematurely stiffening-up within the mixers due to inadequate mixing energy. However, larger batch sizes may be possible in these mixers if modifications are made to the batching process.
- MT-UHPC should be placed at lower temperatures and when material temperatures are low. Elevated temperatures can negatively affect the batching of MT-UHPC, causing the mix to stiffen up significantly due to increased evaporation and premature reactions within the mix. If MT-UHPC is to be placed at elevated temperatures, care should be taken to reduce the risk of the mix

prematurely setting (e.g., using ice to replace a portion of the mix water, storing constituent materials and mixers in the shade).

- Cure temperature should be accounted for when estimating the compressive strength of the material in the field (e.g., using the maturity method), as temperature was observed to significantly affect strength. Compressive strengths were observed to increase with increasing cure temperature, with this effect being most prominent in early strengths (first 48 hours).
- The maturity curves developed in this research may be used to estimate compressive strength of MT-UHPC in the field. These curves were developed under varying curing conditions and were all very similar to each other, especially when using a datum temperature of -5°C. Further research into an appropriate datum temperature may be warranted.

## 8 References

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